OIL SPILL REMOTE SENSING: A REVIEW

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INTRODUCTION

Remote sensing is an important part of oil spill countermeasures. Public expectations with respect to the environment are increasing. The minimum expectation is that the government or the spiller know the location and extent of the contamination. It is also being recognized by spill cleanup personnel that remote sensing can be used to increase spill cleanup efficiency. Furthermore, the advance in electronics has made the instrumentation much cheaper and provides capabilities where none existed before.

The definition of remote sensing implies that a sensor, other than the eye, is used to detect the target of interest at a distance. The most common form of remote sensing as applied to oil spills is aerial remote sensing - that is using aircraft as a platform. Visual observation - irrespective of the platform used, is by definition, not remote sensing. Remote sensing does however, include the use of satellites. This technology will be briefly reviewed in this article along with aircraft-mounted remote sensors.

OPTICAL TECHNIQUES

Optical techniques are the most common means of remote sensing. Cameras, both still and television, are particularly common because of their low price. Aerial mapping is very common and many companies are equipped with aircraft and cameras to perform this function. Many cameras have been commercially available over the past 10 years. Table 1 lists a number of these.[1,2] It is important to note that this and other tables in this paper include sensors that were available in the past, those that are currently available and in some cases, those under development. Many older sensors are still in service and are frequently offered for sale or for use.

The large format cameras listed in Table 1 are largely used for mapping purposes, however are occasionally used for oil spills.

Oil has an increased surface reflectance above that of water in the visible, but also shows some non-specific absorption tendencies to allow use of the visible spectrum as an oil detection means. The visible spectrum is from approximately 400 to 700 nm (blue to red). Oil has several manifestations throughout the spectrum. Heavy oil appears brown, showing up in the 600 to 700 nm region. Mousse shows up in the red-brown or closer to 700 nm. Sheen shows up silvery and reflects light over a wide spectral region up to the blue. There is no strong information in the visible region from 500 to 600 nm, so often this region is filtered out, to give stronger contrast. It should be stressed that oil shows little spectral differences from most backgrounds. Detection in the visible region is also dependent on human pattern recognition as well as the little amount of spectral information.

Experimenters have found that one technique for giving high contrast to visible imagery is to set the camera at the Brewster angle (53 degrees from vertical) and use a horizontally-aligned polarizing filter which passes only that light reflected from the water surface. It is this component that contains the information on surface oil.[1] This technique is said to increase contrast by as much as 100%. Filters that have band-pass below 450 nm also may be used to improve contrast. Figure 1 illustrates the use of a photographic camera in a nadir mode (looking straight down). Figure 2 shows an oblique photograph and illustrates the sun glint that often interferes with this type of photography.

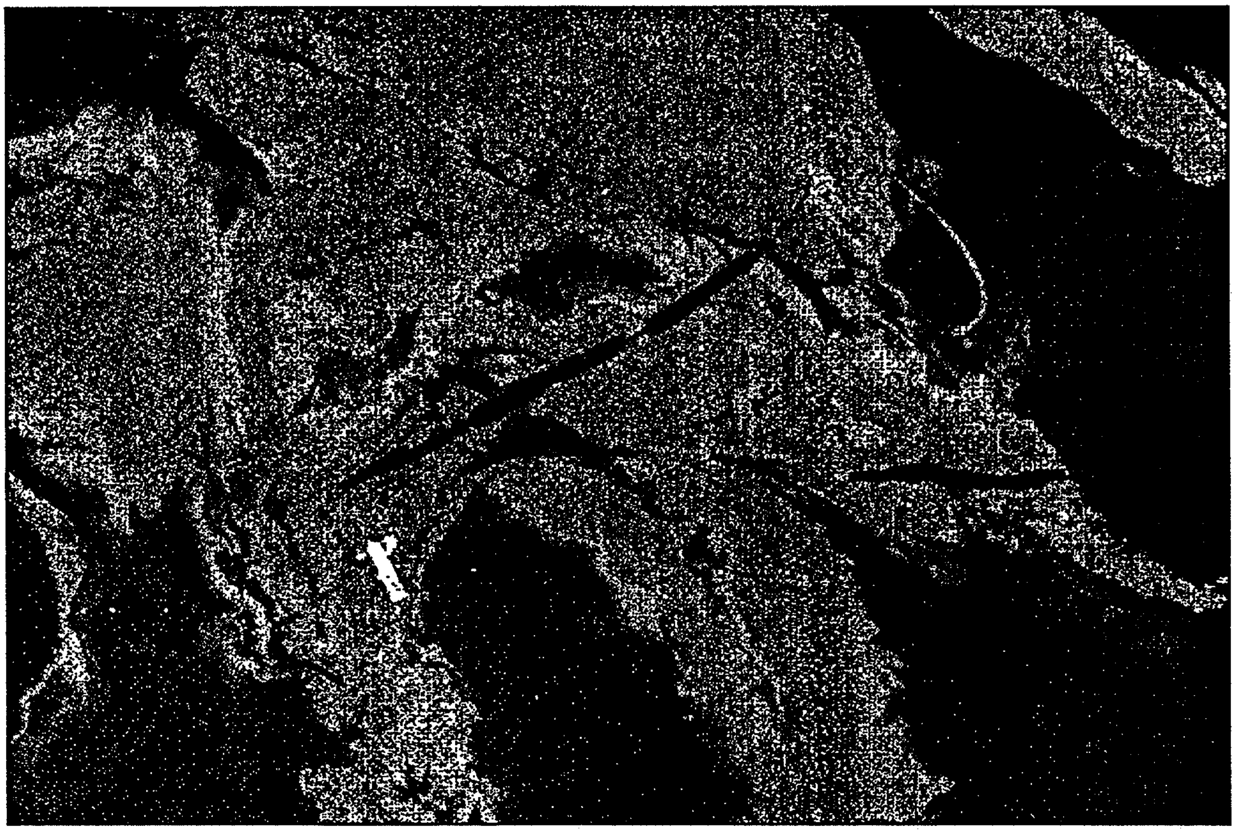

Figure 1 Nadir Photograph of a Slick, Recovery Ship Is About 100 Metres in Length

The use of visible techniques is largely restricted to that of documentation because the lack of a positive oil detection mechanism. Furthermore, many interferences exist. Sun glint and wind sheens can be mistaken for oil sheens. Biogenic material such as surface weeds or sunken kelp beds can be mistaken for oil. Oil on shoreline is difficult to identify positively because weeds can have similar appearance and oil on darker shorelines cannot be detected.

Television cameras are often used. Several systems use filters to improve the contrast, in a manner similar to that noted for the photographic cameras. In the 1970's, when electronics were not highly developed, low-light level television (L^3TV) was used as an inexpensive remote sensor. The advent of charge-coupled device (CCD) detectors in television with their high sensitivity, made low-light-level television obsolescent. An ordinary home video camera has similar sensitivity to the former specially-purchased L^3TV. Filters are sometimes used with television cameras to enhance their utility for oil spill remote sensing, but this technique has limited success, because of poor contrast and lack of positive discrimination.

Figure 2 Oblique Photograph of An Oil Slick

Another visible technique that has not been pursued in recent years is that of laser-illuminated television or active-gated television. The USCG had developed a prototype for their "Aireye" system. The purpose of the unit was to capture pictures of a ship's name. A laser pulse is used to illuminate the field of view and the television is gated to the pulsed laser. Apparently this unit is now commercially available but has not been used for oil spill work.

Scanners are also used as sensors in the visible region of the spectrum. A rotating mirror or prism sweeps the field of view and directs the light to a detector. Before the advent of CCD detectors this method provided much more selectivity and sensitivity than a television camera. The other advantage of using scanners is that signals are digitized and can be processed before display. Figure 3 shows a scanner image of an oil slick. The advantage of using this type of sensor over a regular camera is readily apparent. In recent years, technology has evolved and similar digitization can be achieved without scanning by using a CCD imager and continually recording all elements, each of which is directed to a different field of view on the ground. This type of sensor is known as a push-broom scanner. The advantages of this technology over the older scanning types are many. Several types of abberations and errors can be overcome, units are more reliable than mechanical ones, and all data are collected simultaneously for a given line

TABLE 1 **SOME AERIAL CAMERAS**

Manufacturer	Model	Focal Length (mm)	Coverage (degrees)
9X9 in. OR 23X23 cm. FORMAT CAMERAS			
WILD HEERBRUGG	RC-10	90/150	74/104
JENA	MRB 15/2323	150	74
GALILEO	MODEL VI	150	74
CARL ZEISS	RMK A 8.5/23	85	107
CARL ZEISS	RMK A 15/23	150	74
CARL ZEISS	RMK A 60/23	610	23
FAIRCHILD	T11,T11A	150	74
FAIRCHILD	KC-6A	150	74
FAIRCHILD	F-639	150	74
FAIRCHILD	CA-3-2	150/300/600	74/41/20
FAIRCHILD - GORDON	CA-17	150/300	74/41
HYCAN	K-22A	150/300/600/1016	74/41/20/12
AEROFLEX	KC-3	90	104
9X18 in. OR 23X46 cm. FORMAT CAMERAS			
FAIRCHILD	CA-18	300/600/900	41/20/14
4.5X4.5 in. OR 11X11 cm. FORMAT CAMERAS			
CAI	KA-30A	150	41
CAI	KA-45A	150	41
CAI	KA-50A	45	104
CAI	KS-87A	75/150/300	74/41/21
HYCAN	KS72C-1	75/150/300/450	74/41/21/14
2.25X2.25 in. OR 6X6 cm. FORMAT CAMERAS			
FAIRCHILD	CAX-12	38/75/150/300	74/41/21/10
VINTON	492	38/75	74/41
0.6X0.87 in OR 1.5X2.2 cm. FORMAT CAMERAS			
MITCHELL	KF-8	50/100/150/250	18/9/6/3
4.5 in. OR 11 cm. STRIP CAMERAS (CONVERTIBLE TO 9 in.)			
CAI	CAS-2A	100/175/300/500	60/35/21/12
CAI	KA-18A	75/150	41/74
BILL JACK	S-11	89/150/500	69/74/12
4.5X40 in. OR 11X100 cm. FORMAT PANORAMIC CAMERAS			
FAIRCHILD	KA-59A	300	12x180
PERKIN ELMER	KA-58A	450	14x180
4.5X9.4 in. OR 11X24 cm. FORMAT PANORAMIC CAMERAS			
FAIRCHILD	KA-56A,B	75	73x180
FAIRCHILD	KB-78	75	81x180
2.5X9.4in. OR 6X24 cm. FORMAT PANORAMIC CAMERAS			
PERKIN ELMER	KA-57A	75	41x180
PERKIN ELMER	KA-73	75	41x180
FAIRCHILD	KA-71A	75	40x180
FAIRCHILD	KB-18A	75	40x180

perpendicular to the direction of flight. Scanners and push broom devices are listed in Table 2. Of particular interest are the MEIS (Multi-spectral Electro-optical Imaging Scanner) devices. This series of push broom devices feature relatively narrow band widths and high resolutions. MEIS II has 1024 detector elements, and MEIS FM, currently under development, has 6000 elements, giving it near-photographic quality.

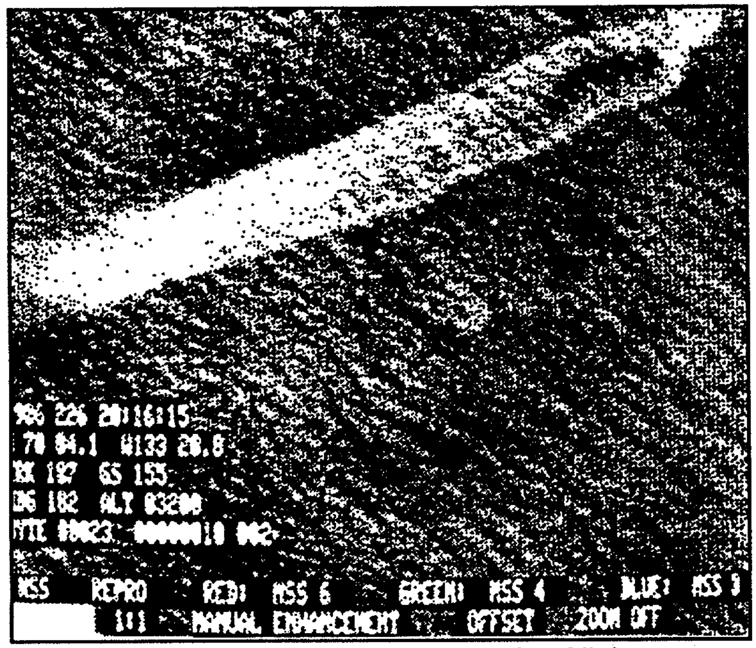

Figure 3 Visible Scanner Image of a Slick

In summary, use of the visible spectrum for oil detection is limited, it does, however, offer economical means of documenting spills and means of providing baseline data on shorelines or relative positions.

INFRARED SENSORS

Oil which is "optically-thick" absorbs solar radiation and reemits this radiation as thermal energy largely in the 8 to 14 micron (8000 to 14000 nm) region. This phenomenon lends itself to oil detection by infrared sensing. This oil appears to be cool in the infrared. Thin oil or sheens are not detected by infrared. In summary, thick oil appears hot or white in infrared data, intermediate thicknesses appear cool and black, and thin oil is not detectable. The thicknesses at which these transitions occur are not known, but scientific evidence indicates that the transition between the heated and cooled layer lies between 50 and 150 microns and the minimum detectable layer lies between 10 and 70 microns. [3-7] The reason for the appearance of the "cool" slick is not fully understood. One theory is that the evaporative cooling of the slick exceeds its radiative heating at a certain thickness and thus appears cool compared to the water. Another and more likely theory, is that a moderately thin layer of oil on the water surface causes destructive interference of the thermal radiation waves emitted by the water, or in some other way attenuates this signal, thereby reducing the amount of thermal radiation waves emitted by the water.[1]

TABLE 2 **LINE SCANNERS**

Manufacturer	Model	Scanner	Width (degrees)	Recorder	Weight (kg)
INFRA-RED SCANNERS					
BENDIX	LM-3	45 deg. PRISM	120	TAPE,FILM	55
DAEDALUS	DE1-100	DBL. 45 MIRROR	120	TAPE,FILM	65
DAEDALUS	DS-1200	45 deg. MIRROR	77	TAPE,FILM	85
HRB SINGER	RECONOFAX VI	DBL. 45 MIRROR	120/140	FILM	75
HRB SINGER	RECONOFAX XIIIA	4-SIDE PRISM	120	FILM	135
TEXAS INSTRUMENTS	RS-310	4-SIDE PRISM	90	FILM	97
TRW HAWKER		4-SIDE PRISM	90	FILM	25
MULTI-SPECTRAL SCANNERS					
ACTRUM	MMS-564K	CONICAL	51	TAPE	79
BENDIX	MMS	45 deg. MIRROR	60	HI-DEN. TAPE	1300
DAEDALUS	1230	45 deg. MIRROR	77	TAPE	54
DAEDALUS	1260	45 deg. MIRROR	86	TAPE	129
TEXAS INSTRUMENTS	RS-14	4-SIDE MIRROR	60	CRT. FILM	120
PUSH-BROOM MULTI-SPECTRAL DEVICES					
ITRUS	CASI	PUSH-BROOM	40	TAPE	30
CCRS	MEIS I	PUSH-BROOM	24	TAPE	46
MDA	MEIS II	PUSH-BROOM	45	TAPE	
MDA	MEIS FM	PUSH-BROOM	60	TAPE	

TABLE 3 **THERMAL INFRARED CAMERAS/SYSTEMS**

Manufacturer	Model	Cooling	*Wavelength* (µm)	Weight (kg)
FLIR OR FORWARD LOOKING INFRARED SYSTEMS				
FLIR SYSTEMS	L300 3	J-T CRY.	10.4	
FLIR SYSTEMS	L300 4	J-T CRY.	10.4	
FLIR SYSTEMS	L300 4A	J-T CRY.	10.4	
FLIR SYSTEMS	L300 4B	J-T CRY.	10.4	
HONEYWELL	WA8A17	J-T CRY.	7.5-11.5	
LOCKHEED	68-69	J-T CRY.	10	
AEROSYSTEMS	AEROFLIR	J-T CRY.	8.0-12.0	
GENERAL PURPOSE CAMERAS				
BARR & STROUD		J-T CRY., AIR	8.0-14	10
SMALL GENERAL PURPOSE INDUSTRIAL CAMERAS				
GEN. ELECT.	EEV	NONE	7.-12	0.5
BOOTH	FIND-R-SCOPE	NONE	5.-12	0.7
AGEMA	THERMOVISION	J-T CRY.	5.-13	1
HUGHES	PROBEYE 7300	ELECTRIC	2-5.6	3
HUGHES	699	ELECTRIC	2-5.6	3
HUGHES	686	GAS	2-5.6	4
HUGHES	664	ELECTRIC	2-5.6	3
HUGHES	650	GAS	2-5.6	3

NOTE: J-T = JOULE-THOMPSON COOLING

Figure 4 A High Resolution MEIS Image of Prince William Sound

Infrared cameras are now very common and several commercial units are available as listed in Table 3. In past years scanners with infrared detectors were largely used. Some of these units are detailed in Table 2. Infrared detectors of any type suffer from the disadvantage that their detectors require cooling to avoid thermal noise, which would destroy any useful signal. The traditional method of cooling the detector was by liquid nitrogen. This generally gives about 4 hours of service. New, smaller sensors can use electric thermal coolers or Joule-Thompson coolers which use the cooling effect realized when a gas is expanded. This type of cooling implies that a gas cylinder or compressor be transported with the sensor but refills or servicing may not be required for days at a time.[8]

Most infrared sensing takes place at what is known as the thermal infrared at the wavelengths 8 to 14 microns. Figure 5 and 6 illustrate the usefulness of infrared imagery in oil spill work. Figure 8 shows the same slick as shown in Figure 7, but as a photographic image. Only limited work has been done in the 3-5 micron region. Many new sensors are, however, available with this spectral region.

One sensor which is designed as a fixed-mounted unit uses the differential reflectance of oil and water at 2.5 and 3.1 microns.[9]

The relative thickness information in the infrared is useful because it can be used to direct countermeasures equipment to thicker portions of the slick. Oil detection in the infrared is not positive, because several false targets can interfere - including weeds, shoreline, and oceanic fronts. Infrared is, however, somewhat economical and is currently the prime tool used by the spill remote sensor.

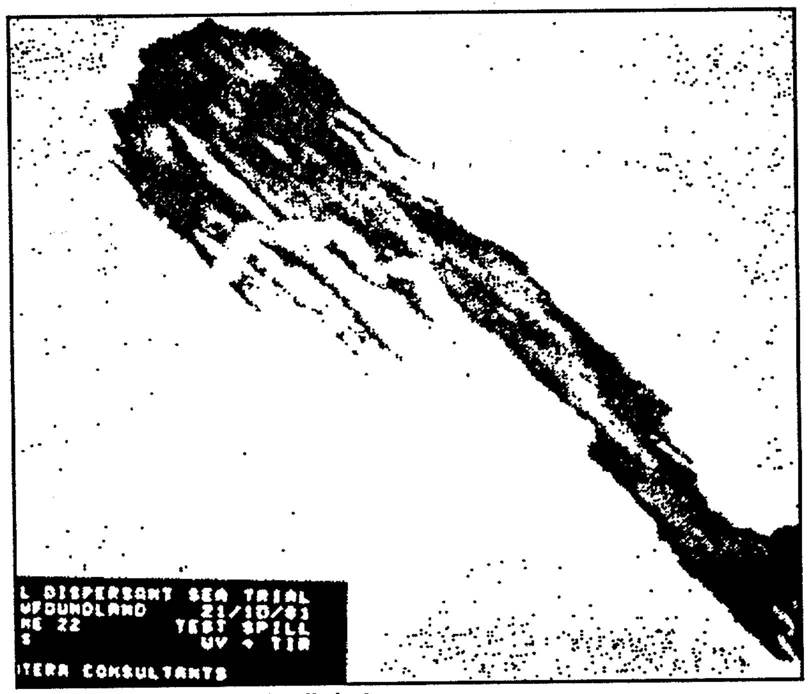

Figure 5 Infrared Slick Image

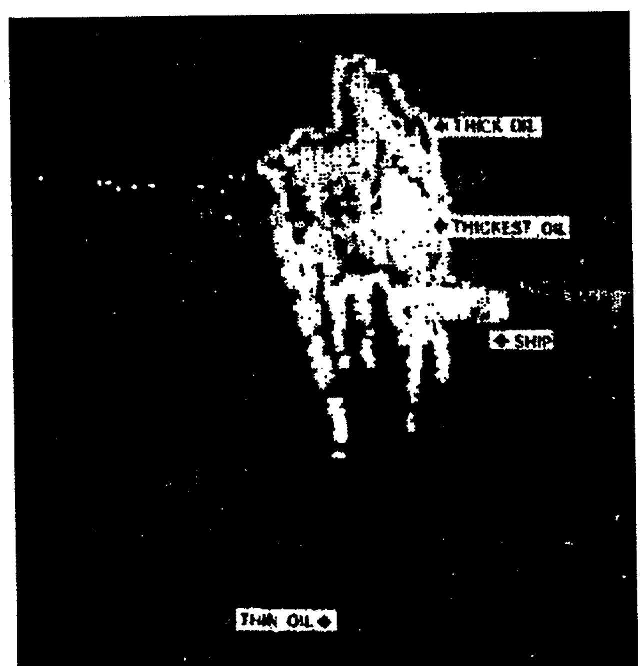

Figure 6 Thickness Maps Produced Using IR and UV

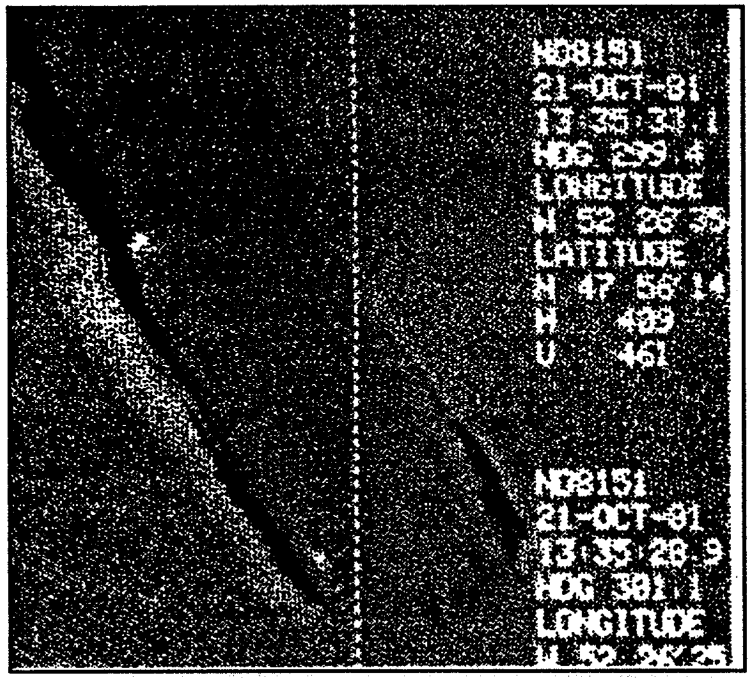

Figure 7 Infrared Image of A Treated Oil Slick

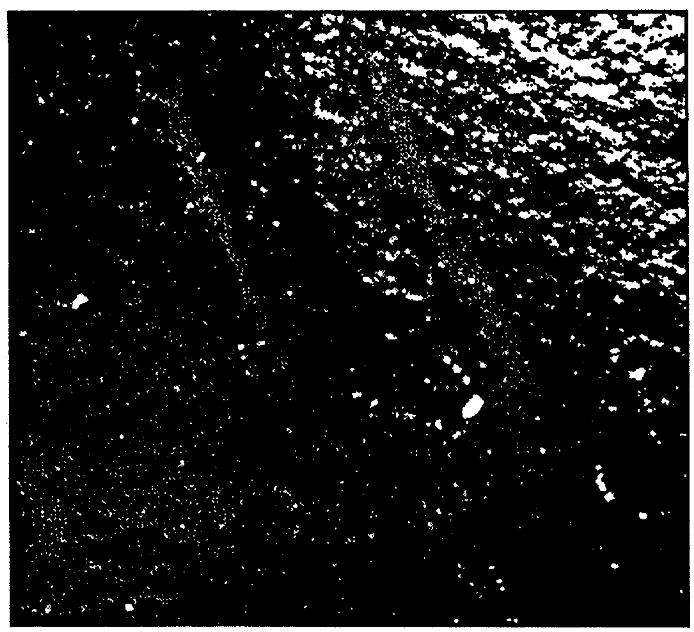

Figure 8 Photograph of The Same Slick as Shown Above

ULTRAVIOLET SENSORS

Oil slicks display high reflectivity of ultraviolet radiation even at thin layers (<0.01 microns). Ultraviolet sensors can be used to map even thin sheens of oil. Overlapped ultraviolet and infrared images are often used to provide a relative thickness map of spills. Ultraviolet cameras, although inexpensive, are not used to a great extent because it is difficult to overlay camera images.[8] Scanner data and push-broom scanners allow for the easy superimposition of data and the production of IR/UV overlay maps. Ultraviolet data is also subject to many interferences or false images such as wind slicks, sun glints, and biogenic material. Because these interferences are often different than those for infrared sensing, the combination of IR and UV can provide a more positive indication of oil than the use of either technique alone.

FLUOROSENSORS

Fluorosensors employ the property that some compounds in the oil absorb ultraviolet light and re-emit part of this energy in the visible. Since very few other compounds show this tendency, fluorescence is a strong indication of oil presence. Natural fluorescing substances such as chlorophyll, fluoresce at sufficiently different wavelengths to avoid confusion. There is, however, a phenomenon known as "gelbstoff" which consists of a broad spectrum of fluorescing materials. This background changes very slowly along the sensor path and thus can be compensated for rather easily. Different types of oil yield a slightly different fluorescent response. It is possible to differentiate between heavy and light oil under ideal conditions. This property is currently useful only as a scientific tool. Figures 9 and 10 show signals from older instruments.

Most laser fluorosensors employ a laser operating in the ultraviolet region between 340 and 300 nm.[1,10] With this wavelength of activation, there exists a broad organic matter fluorescent return, centred at 420 nm. This is the Gelbstoff or yellow matter, which can be easily annulled. Chlorophyll yields a sharp peak at 685 nm. Oil fluorescent return is in the region between 400 to 550 nm with peak centres in the 480 nm region. There also exists a phenomenon known as Raman Scattering, which involves molecular reaction between the incident light and the water molecules on the surface. The water molecules can absorb some of the energy as rotational-vibrational energy and return the light as the incident energy less this energy of rotation or vibration. The water Raman signal occurs at 344 nm when the incident wavelength is 308 nm. The water Raman is useful for maintaining calibration of the fluorosensor in operation, but had also been used in a limited way to estimate oil thickness, because oil on the surface will suppress the water Raman signal in proportion to thickness.[11] The point at which the Raman signal is entirely suppressed is not known, and each oil type has a different absorption parameter. Therefore it is difficult to employ water Raman suppression as a thickness sensor.

It is also possible to use the principle of oil fluorescence on a small scale. Work has been done to develop the use of a hand-held UV light to detect oil spills at night at short range.[12]

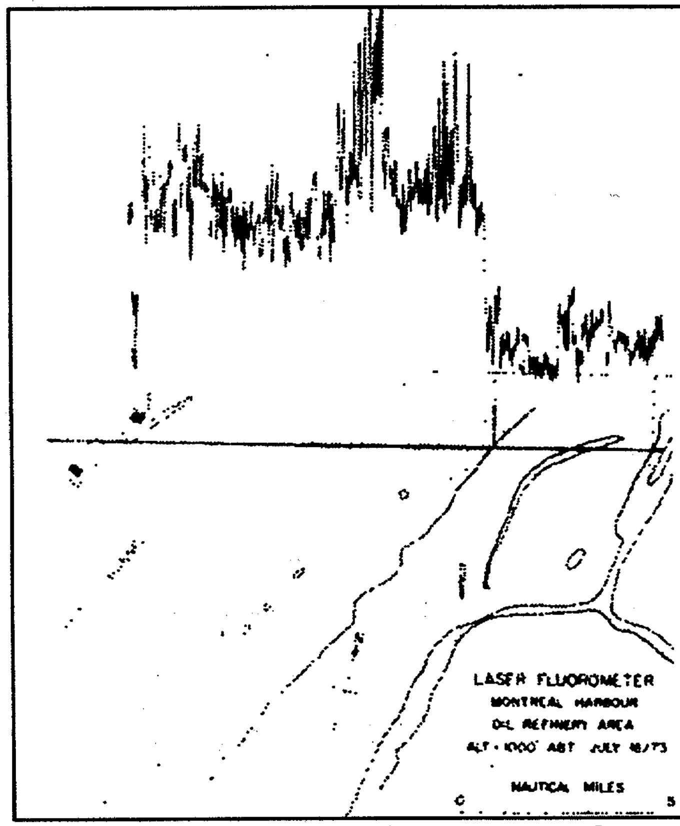

Figure 9 Fluorescent Signal Return Over A Slick in Montreal Harbour

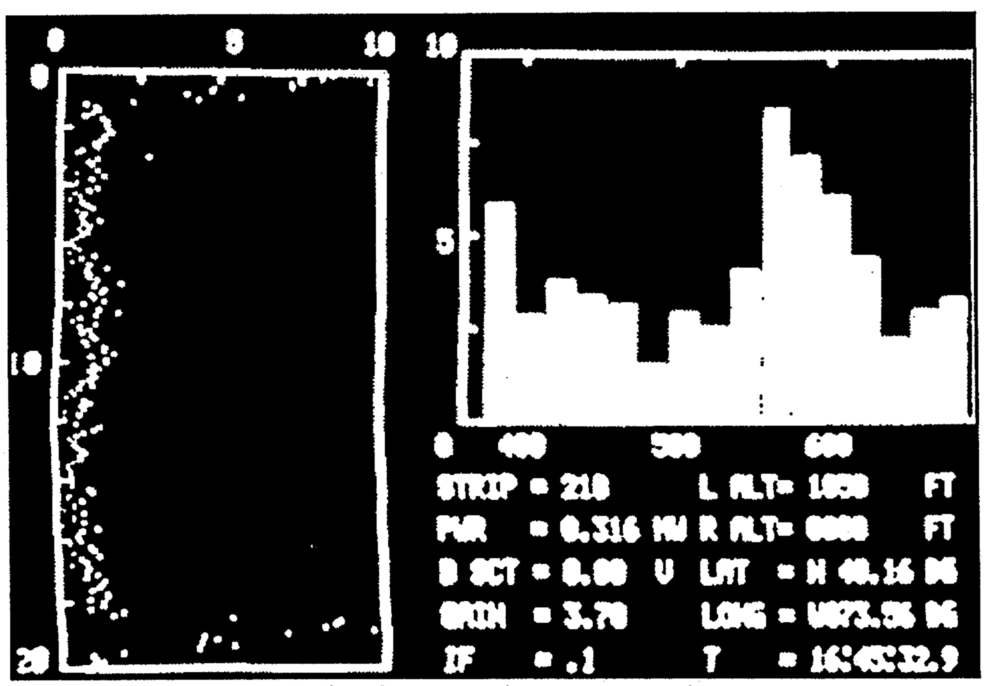

Figure 10 Photograph of Laser Fluorosensor Instrument Screen Showing Signal Strength and Spectrum

Another related instrument is the "Fraunhofer Line Discriminator" which is essentially a passive fluorosensor using solar irradiance instead of laser light.[1] This instrument did not attain great success because of the limited discrimination and the poor signal-to-noise ratio. Laser fluorosensors are thought to have significant potential for the future because they may be the only means to discriminate between oiled and un-oiled weeds and detecting oil on a variety of beach types. Additionally, the sensor offers the only means of detecting oil on or snow.

Development continues on laser fluorosensors, as the ideal instrument has still not been built. Table 4 provides details on some current and future instruments.

TABLE 4 **LASER FLUOROSENSORS**

Manufacturer	Model	Laser			Number of Channels
		Type	Wavelength (nm)	Power (w)	
Oldenburg	curent	Eximer	308	10	4/5
		dye	450/533	1	4/5
Oldenberg	proposed	Eximer	308	10	12
Italian	current	Nitrogen	337	3(CW)	1
Barringer	MK III	Nitrogen	337	5	16
Barringer	FLUOROSCAN	Eximer	308	10	4
British Petroleum	current	Eximer	308	10	4
Barringer	LEAF(MK IV)	Eximer	308	10	64
		dye	540	2	64
Barringer	proposed	Triple-YG	366	20	64

MICROWAVE AND RADAR

RADAR

Oil on a sea surface damps some of the small capillary waves. Since these capillary waves reflect radar energy producing a "bright" image known as sea clutter, the presence of an oil slick can be detected as a "cold" sea or one which has an absence of this sea clutter. Unfortunately oil slicks are not the only phenomenon which is detected in similar manner. Interferences are many and include fresh water slicks, wind slicks (calms), wave shadows behind land or structures, weed beds which calm the water just above them, glacial flour, biogenic oils, whale and fish sperm. Because of the number of these interferences, radar can be useless in situations such as in Prince William Sound where the dozens of islands, fresh water inflows, ice, and other features yield literally hundreds of false targets. Radar is, despite these limitations, an important tool for oil spill remote sensing because it is the only useful sensor for large area searches, as will be demonstrated later, and because it is one of the few sensors that can "see" at night and through clouds or fog.

The usefulness of radars in conducting large-area searches is illustrated in Table 5. This table gives comparisons of different sensor options in searching for lost-cargo-type spills. A ship will sometimes, reach its destination or a point in its journey and the crew discovers that it has lost part of its cargo. One of these situations involved the KURDISTAN tanker which broke in half, but due to the differential drift between the ship halves and the oil, the location of the lost cargo was unknown until found by remote sensing techniques. Table 5 illustrates that the only practical means of searching for this cargo is to use a wide-range radar and a jet airplane. Use of limited-range radars is not a practical means for performing this function.

Table 5 **Times to Cover Search Area Entirely For Three Historic Situations**

Aircraft and Sensors	Time in Days to Cover Area		
	KURDISTAN	PETER STUYVESANT	Davis Strait
Propeller and UV/IR	2	60	110
Propeller and sm. radar	1	23	42
Jet and small radar	1/5	5	8
Jet and STAR radar	1/20	1	1

Two basic types of radars have application to oil spills and general environmental remote sensing, SARs or synthetic aperture radars and SLARs or Side-Looking Airborne radars. The latter is an older technology, but cheaper, and employ long antennae to try to improve spatial resolution. The synthetic aperture radars use the forward motion of the airplane to synthesize a very long antenna, thereby achieving very good spatial resolution at the expense of sophisticated electronic processing. SARs are more costly, but are capable of much more range and much greater resolution than SLARs. Radar equipment having application to oil spills is listed in Table 6.

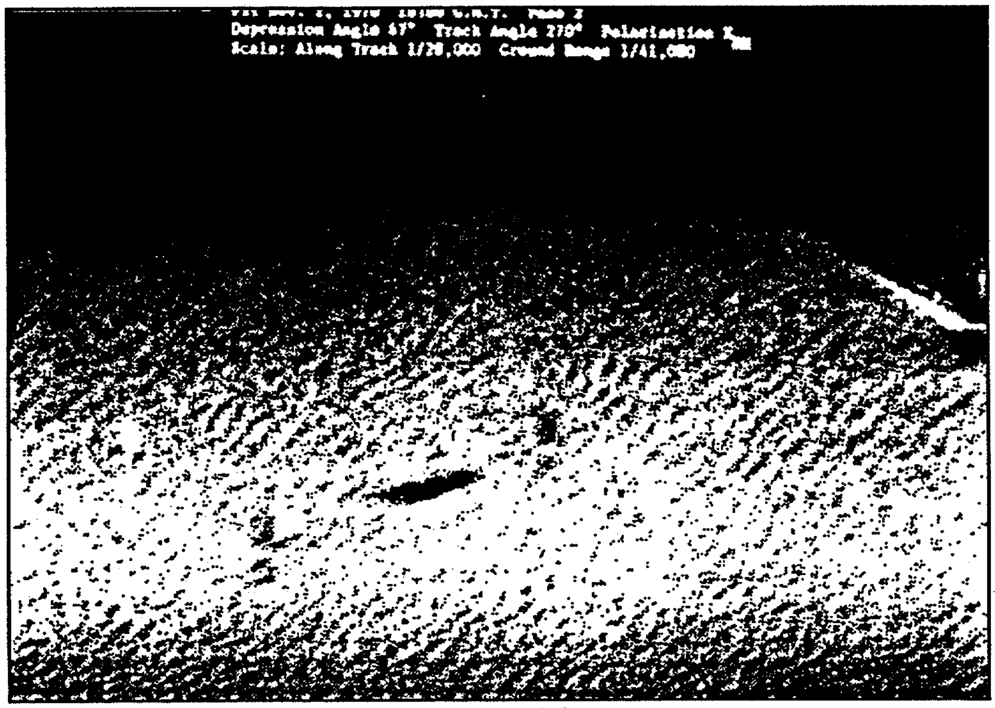

Figure 11 Radar Image of A Test Slick

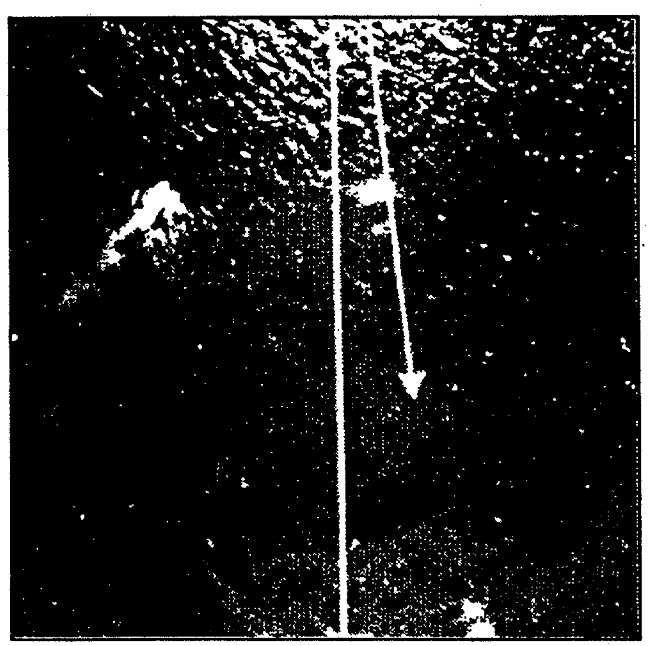

Figure 12 Photograph of The Same Slick

TABLE 6 RADARS/MICROWAVE DEVICES

Manufacturer	Model	Band	Polarization	Power (peak, kW)	Maximum Range (km)	Maximum Resolution (m)	Weight (kg)
SIDE-LOOKING REAL-APERTURE RADARS							
ERICKSON		X	V/V	10	20	7.5 x range	76
MOTOROLA	APS-94D	X	H or V	200	24-40,80	1.7 x range	235
EMI	F391	X	H or V	100	15,30	3.5 x range	195
CAL	SLAR-100	X	H/H		25,50,100		
WESTINGHOUSE	APD-7	C	H/H	50	8	1.7 x range	225
SIDE-LOOKING SYNTHETIC -APERTURE RADARS							
ERIM		X,L,C	full polarimeter	250	24	1.5	1635
GOODYEAR	APQ-102	X	X	1-X,5-L	37	1.5 x range	232
JPL	DC-8	P,L,C	full polarimeter	60,67,61		4 x 11	
MDA	CCRS	C,X	H or V	C-3.4,X-3.8	62	0.8 x 6	1360
MDA	STAR I	X	V/V	500	70	4-30	250
MDA	STAR II	X	V/V	500	120	4-25	300
MDA	ENV	X	V/V	250	70	6-30	150
RADAR SCATTEROMETER					ANGLE		
RYAN	720	Ku	H or V	0.002	-60 to + 60	20x20	16
MPB		C	H or V	0.005	-60 to + 60	20x20	
PASSIVE MICROWAVE IMAGERS							
SWEDISH SPACE		35 GHz		-		2,4 °	29
MPB	AIMR	37,90 GHz	H or V	-	-60 to + 60	1°	~100
TRW		6-CH	H or V	-	-60 to + 60	-	~100

Experimental work on oil spills has shown that X-band radar yields better data than L or C band radar. In addition, it has been shown that antenna polarizations of vertical for transmission and vertical for reception (VV) also yield better results than other configurations. [1,13,14] Radars are thought to be limited by sea state, too low sea states will not produce sufficient sea clutter in the surrounding sea to contrast to the oil and very high seas will scatter radar sufficiently to block detection inside the troughs. Detailed work on sea state limits has not been done but cases of both extremes have been documented in the literature. [1,15] Personal communication with radar operations scientists have indicated that winds of between 10 to 30 km/hr provide the best conditions for radar detection of oil in the sea.

Search radars such as frequently employed by the military have little - if any - application to oil spills because they frequently remove the clutter signal. Thus, the primary signal of interest is deleted. Furthermore these radars have signal processing optimized to pinpoint small, hard (to radar signals) objects such as periscopes. This signal processing is very detrimental to oil spill detection.

Ship radars suffer from similar limitations and have the additional limitation of low altitude that restricts their theoretical range to between 8 to 30 km., depending on antenna height. Ship radars can be adjusted to decrease the effect of sea clutter de-enhancement. Ship-borne radars were successfully used at 8 km. to detect a surface slick in the Baltic and during a trial offshore Canada at a maximum range of 17 km.[16] The technique is highly limited by sea state and, in all cases where it was used, the presence and location of the slick was already known.

In summary, radars optimized for oil spills can provide useful application to spill remote sensing, in particular for large area searches and for night-time or foul weather work.

MICROWAVE SCATTEROMETERS

A microwave scatterometer is a device that measures the scattering of microwave or radar waves by the target surface. The presence of oil reduces the scattering of the radar signals just as it does for the radar sensors and therefore suffers the large number of interfering factors noted above. One radar scatterometer was flown over several slicks and employed a low-power transmitter operating in the Ku band (13.3 Ghz).[1] The advantage of this type of sensor is that it has a similar aerial coverage to optical sensors and has a nadir aspect (looks straight down). The disadvantages of the sensor include the lack of discrimination for oil and the lack of imaging capability.

MICROWAVE RADIOMETERS

The ocean is an emitter of microwave radiation. Oil on the ocean is a strong emitter of microwave radiation compared to water and thus appears as a bright object on a darker sea. Water has an emissivity factor of 0.4 compared to oil of 0.8.[1] A passive device can detect this emission and could provide a detection means for oil. Furthermore there is a signal change with thickness and, in theory, the device could measure thickness. This detection method has been tried over the years, but generally has not resulted in great success. First, the methodology depends on knowing many environmental and oil specific parameters and second, the signal return is dependant on signal strength but in a cyclical fashion.[3] A given signal strength can imply any one of two or three signal film thicknesses within a given slick. Some newer devices employ 2 or 3 different signals to predict slick thicknesses more accurately. Emission of microwaves is a maximum when the effective thickness equals an odd multiple of a quarter wavelength of the observed energy. The method suffers from other weaknesses as well. Biogenic materials also interfere and the signal-to-noise ratio is poor. The methodology does not appear to work at all on water-in-oil emulsions.[3] Scanning radiometers are necessary to produce a thickness map, but scanning with this device is difficult. The Swedish Space agency has done a some work with different systems, primarily a dual band, 22.4 and 31

Ghz, device, also with a single band 37 GHz device.[17] Tests of the devices have achieved only mixed results.

In summary, passive microwave radiometry does not appear to offer potential as a slick thickness measurement device. Extensive work using multiple frequencies is on-going.

SLICK THICKNESS SENSORS

There exists a need to measure oil spill thickness. First, no reliable methods exists and the basic physics of oil spreading and behaviour are not well understood. The ability to measure slick thicknesses would, no doubt, result in significant advances in the understanding of spill behaviour and effects, and improve our ability to deal with them. There does not exist a reliable laboratory method to measure thin slicks at this time. Second, there is strong motivation to develop a slick thickness sensor so that the effectiveness of certain countermeasures such as dispersants can be measured. The volume of oil remaining on the water cannot be measured without such a device.[18] Finally, there is strong motivation to determine the amount of oil in fugitive slicks. Aircraft surveillance of slicks often results in erroneous oil quantity estimates. The variances of measuring slick thickness using a combination of sensor data and visual estimates, is illustrated in Table 7. This table contains the results of a field trial to assess oil slick volume using existing aerial techniques.

The use of the water Raman peak in laser fluorosensor data discussed above has not been exploited or tested fully.[11] This technique may work for thin slicks, but probably not for thick ones. Attempts to calibrate the thickness appearance of infrared imagery have been made, but also have not been successful.[5,6] It is suspected that the temperatures of the slick as seen in the IR are highly dependent on oil type, sun angle and weather conditions. If this is the case, it is not be possible to use IR as a calibrated thickness measurement tool. Accurate surface methods do not exist, therefor the calibration of existing equipment is very difficult.[19] The use of sorbent techniques to measure surface thickness yields highly variable results.[18] As noted in the discussion of the microwave radiometers above, the signal strength as measured by these instruments can imply one of several thicknesses. This methodology will require much more assessment before judging whether it does or does not have capability for slick thickness measurement.

A variety of electric, optical and acoustic techniques were investigated to measure oil thickness.[20] Two promising techniques were pursued in a series of laboratory measurements. The first technique is known as "thermal mapping".[21] A laser is used to heat a region of oil and the temperature profiles created over a small region near this heating is examined using an infrared camera. The temperature profiles created are dependant on the thickness. An even more promising technique is a "laser acoustic" one.[22] An infrared carbon dioxide laser is used to heat the oil layer. This sets up thermal and acoustic waves in the oil. The acoustic waves can be detected using another laser and an interferometer. The thickness can be determined from the time of propagation of the acoustic wave between the upper and lower surfaces of the oil slick. This is a very reliable means of studying oil thickness and offers great potential. A consortium of agencies including Esso Resources Canada, Environment Canada, the United States Minerals Management Service, and the American Petroleum Institute is pursuing the technology. Laboratory tests are planned to investigate the effect of waves and distance. If all goes well, the system will be flown in the near future to test it under real conditions.

TABLE 7 **RESULTS OF THE NIFO TRIALS**

Product spilled	Quantity (cu. metres)	Country Airplane - Amount Reported				
		Germany	UK	Norway	Holland	Sweden
Marine Fuel	1	1	0.25	12	0.1	1
Crude	5	4	0.2	15	0.04	8.1
Mousse	2.1	2	-	7	0.02	1.6
Drilling Fluid	5	-	-	-	-	-
Diesel Fuel	1	1	-	-	-	-
Condensate	0.02	2	-	-	0.05	-
SENSORS ON BOARD MWR=MICROWAVE RADIOMETER		SLAR IR/UV MWR	SLAR IR/UV	IR/UV	SLAR IR/UV	SLAR IR/UV MWR

REMOTE SENSING OF OIL UNDER UNIQUE CIRCUMSTANCES

OIL-IN-WATER

The only instrument capable of remotely measuring oil in the water is the laser fluorosensor. One instrument, the Fluoroscan, was built specifically for this application. The system operates in a similar manner to that of a normal fluorosensor, except that only that signal derived from fluorescence in the water column is analyzed. The depth of penetration is thought to be a maximum of 6 metres. Because of the attenuation of the water column, sensitivity decreases logarithmically downwards from the water surface.

Another instrument that holds potential for detecting neutrally-buoyant oil is the Lidar bathymeter. This instrument uses a laser in the green region to map bottom contours. Presence of massive amounts of oil floating beneath the surface would, in theory, be detected.

OIL-ON-ICE

Oil has been detected on ice using visible techniques.[1] Oil appears to be black or brown against the white background of the ice. Sediment also has the same appearance and constitutes the major interference. Microwave techniques have been tried but were not successful because of the strong emissivity of the ice.[14] Microwave radiometry is, however, very useful in discriminating between first and multi-year ice. The best potential for positively identifying oil on ice resides in the laser fluorosensor.

OIL IN OR UNDER-ICE

Extensive work was done in this area by Esso Resources and Environment Canada. Examination of non-contact techniques such as the use of radar showed that this technique did not have potential.[23] A contact technique using acoustic means to detect the oil was developed to the prototype testing stage.[24,25] The technique uses the phenomenon that oil appears to be a solid to a sound wave. Liquids propagate shear and pressure waves (two different types of sound waves) in different ways. By examining the ratio of shear and pressure waves, one can find out if oil is present in or under the ice and even at what depth. The methodology requires further testing and development before proceeding to commercialization.

OIL-AMONGST-ICE

Oil amongst ice has been detected and mapped by both UV and IR techniques, however its location was already known.[1] This technique will work for situations where there is much oil and a large amount of open water. In most situations, the best potential for detection is offered by the laser fluorosensor.

REAL TIME DISPLAYS AND PRINTERS

A very important aspect of remote sensing is the production of data so that operations people can quickly and directly use it. Real time displays are very important so that the remote sensor operators can adjust instruments directly in flight and so that they can provide information quickly on the location or state of the spill.

In 1980, the Canada Centre for Remote Sensing, with support from Environment Canada, developed the first generic real-time display (generic = compatibility with different sensors). The unit, known as the Norpak, provided a good deal of service displaying multispectral, IR and UV data. A series of devices under the trademark, ALICE, have been built by Knudsen Engineering. These devices are also used to display electro-optical data. A new device built by the same firm will allow the display of radar data along with optical data.

No printing devices are commercially-available for electro-optical data. The current expectation is that map-like data should be available upon landing after the remote sensing flight. Technology is available for this, however, development is required.

SATELLITE REMOTE SENSING

The use of satellite remote sensing for oil spills has been attempted several times. The slick from the IXTOC I well blowout in Mexico was detected using GOES and also by the AVHRR (Advanced Very High Resolution Radiometer) on the LANDSAT satellite.[1] Subsequently a blowout in the Persian Gulf was detected. The massive EXXON VALDEZ slick was detected on SPOT satellite data. Oiled ice in Gabarus Bay resulting from the KURDISTAN spill was detected using LANDSAT data.[26,27] The recent spill in the Arabian Gulf during the war was detected by several satellites. The KURDISTAN oil-in-ice is shown in Figure 13. It is significant to note that in all these cases the position of the oil was known and in all cases, data had to be processed to see the oil. Data processing always lasted several weeks.

Satellite sensors having some application to oil spills, are listed in Table 8.[28] Only SPOT and LANDSAT are active at this time.

There are several problems in reliance on satellite remote sensing. The first is the frequency with which overpasses occur. The second is the absolute reliance on clear skies to perform optical work. These two factors combined can give a very low probability of seeing a spill on satellite data. The case of the EXXON VALDEZ spill illustrates this well. Although vast amounts of ocean were covered by the spill for over a month, only one clear day and a satellite overpass occurred, that on April 7. The third disadvantage of satellite remote sensing is the difficulty in developing algorithms to highlight the oil slicks and the long time to do so. It took over two months in the case of the EXXON VALDEZ spill before the first group managed to "see" the oil slick in the satellite imagery, although its location was precisely known.

Optical satellite imagery does not offer much potential for oil spill remote sensing. The new European radar satellite and the Canadian RADARSAT may offer some potential for large offshore spills.

TABLE 8 **SATELLITE SYSTEMS**

Satellite	Sensor	End of Life (year)	Period (days)	Swath Width (km)	Maximum Resolution (m)	Bands/ Centre (nm)
NIMBUS	CZCS COASTAL ZONE COLOR SCANNER	1982	1		825	1--443 2-520 3-550 4-670 5-750 6-11500
	AVHRR ADVANCED VERY HIGH RESOLUTION RADIOMETER	199X	1	1600	1000/4000	5-580 to 12500
GOES	VISSR VISIBLE AND INFRARED SPIN SCAN SPECTROMETER	199X	STATIONARY		8000	1-630 2-11000
LANDSAT	MSS	1989	16 FULL REPEAT	185	80	1-550 2-650 3-750 4-925 5-11000
	TM THEMATIC MAPPER	1989	16 FULL REPEAT	185	30/120	1-4 from 450 to 900 5-1600 6-2200 7-11000
SPOT	SPOT	199X	2.5	60/117	10/20	1-550 2-650 3-840 P-620
SEASAT	SAR	1983	0.5	40	25	C RADAR
ERS-1	SAR	1991+	3	80	30	C RADAR
JERS-1	SAR	1992+		75	18	L RADAR
RADARSAT	SAR	1994+	3	60/500	8/100	C or L RADAR

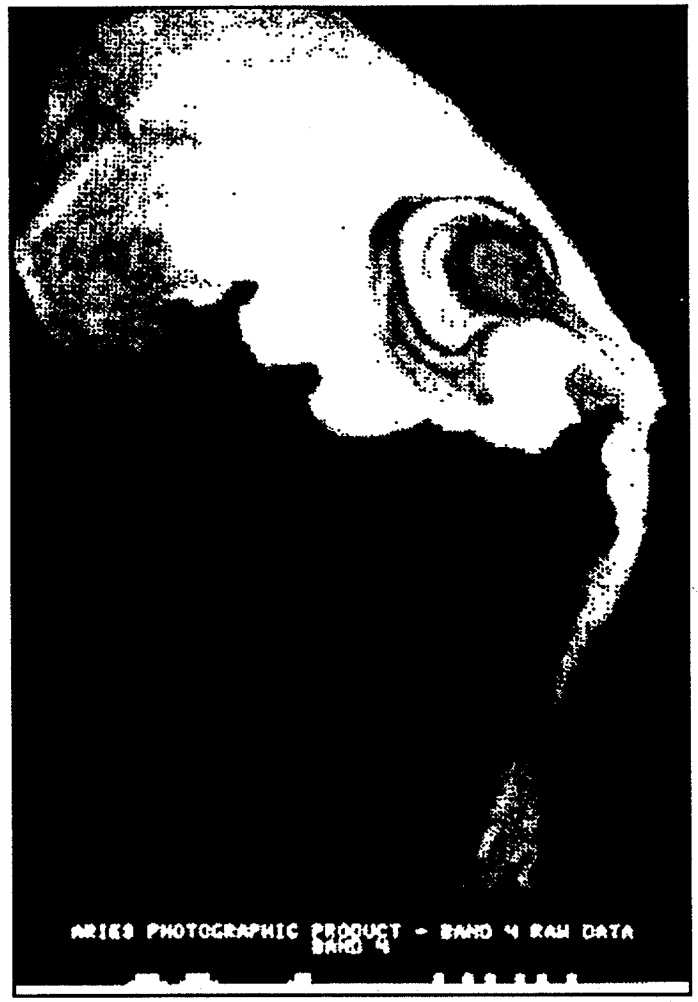

Figure 13 Satellite Image of Oil On Ice in Gabarus Bay, Streaks in Centre of White Ice Patch Are Oil, Outer Material is Sediment

SUMMARY RECOMMENDATIONS

The first sensor recommended for oil spill work is an infrared camera. This is the cheapest and most applicable device. A camera and ancillary equipment can be purchased for under $100,000 and weighs less than 50 kg. This is the only piece of equipment that can be purchased off-the-shelf. All other sensors require special order and often, actual development. The laser fluorosensor is the second sensor recommended as it offers the only potential for discriminating between oiled and un-oiled weeds or shoreline, and for positively identifying oil pollution on ice and amongst ice. This instrument however is large and expensive. A production unit could cost $750,000 and weigh 200 kg. The third sensor recommended is an UV and visible device. These devices vary a good deal in price, size and state of development.Radar, although low in priority for purchase, offers the only potential for large area searches and foul weather remote sensing. SAR is recommended and a unit will cost about $1,000,000 and will require a dedicated aircraft. Most other sensors are experimental or do not offer good potential for oil detection or mapping.

Whatever sensor is purchased, the equipment package should always include a real time display and printer as well as a photographic camera for documentation purposes.

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REFERENCES

1. O'Neil, R.A., R.A. Neville and V. Thompson, The Arctic Marine Oilspill Program (AMOP) Remote Sensing Study, Environment Canada Report Number EPS 4-EC-83-3, Ottawa, Ontario, 257 p., 1983.
2. Bercha, F.G. and Associates, Remote Sensing Equipment for Chronic Oil Discharges, Environment Canada Report Number EE-54, Ottawa, Ontario, 1984.
3. Hurford, N., "Review of Remote Sensing Technology", in The Remote Sensing of Oil Slicks, A.E. Lodge, Ed., John Wiley and Sons, Chichester, United Kingdom, p.7-16, 1989.
4. Goodman, R.H., "Application of The Technology in North America", in The Remote Sensing of Oil Slicks, A.E. Lodge, Ed., John Wiley and Sons, Chichester, United Kingdom, p.39-65, 1989.
5. Belore, R.C. Calibration of Infrared Imagery Using a Surface Sampling Device, Environment Canada unpublished report, 1983.
6. Belore, R.C., "A Device for Measuring Oil Slick Thickness", Spill Technology Newsletter, 7(2), p.44-47, 1982.
7. Neville, R.A., V. Thompson, K. Dagg and R.A. O'Neil, "An Analysis of Multispectral Line Scanner Imagery From Two Test Spills", in Proceedings of First Workshop Sponsored by Working Group I of the Pilot Study on The Use of Remote Sensing for the Control of Marine Pollution, NATO Challenges of Modern Society, Vol. 6, p.201-215, 1979.
8. Goodman, R.H., Simple Remote Sensing System For The Detection of Oil on Water, Environmental Studies Research Fund Report number 98, Ottawa, Ontario, 31 p., 1988.
9. Seakem Oceanography, Remote Sensing Chronic Oil Discharges, Environment Canada Report EE-108, 46 p., 1988.
10. Diebel, D., T. Hengstermann, R. Reuter and R. Willkomm, "Laser Fluorosensing of Mineral Oil Spirits", in The Remote Sensing of Oil Slicks, A.E. Lodge, Ed., John Wiley and Sons, Chichester, United Kingdom, p.127-142, 1989.
11. Hoge, F.F. and R.N. Swift, "Oil Film Thickness Measurement Using Airborne Laser-Induced Water Raman Backscatter", Applied Optics, 19(19), p. 3269-3281, 1980.
12. Fingas, M.F., "A Simple Night Time Oil Slick Detector", Spill Technology Newsletter, 7(1), p. 137-141, 1982.

13. Intera Technologies, Radar Surveillance in Support of the 1983 COATTF Oil Spill Trials, Environment Canada Report Number EE-51, 48 p., 1984.
14. C-CORE (Centre For Cold Ocean Resources Engineering), Microwave Systems for Detecting Oil Slicks in Ice-Infested Waters: Phase I - Literature Review and Feasibility Study, Environment Canada Report Number EPS 3-EC-81-3, 353 p., 1981.
15. Hielm, J.H., "NIFO Comparative Trials", in The Remote Sensing of Oil Slicks, A.E. Lodge, Ed., John Wiley and Sons, Chichester, United Kingdom, p.67-75, 1989.
16. Tennyson, E.J., "Shipborne Radar As An Oil Spill Tracking Tool", Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, Ontario, p. 385-390, 1985.
17. Fast, O., "Remote Sensing of Oil on Water - Air and Space-Borne Systems", Proceedings of the DOOS Seminar, SINTEF, Trondheim, Norway, 1986.
18. Goodman, R.H. and M.F. Fingas, "The Use of Remote Sensing for The Determination of Dispersant Effectiveness", Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, Ontario, p. 377-384, 1988.
19. Brown, H.M. and R.H. Goodman, "In-Situ Burning of Oil in Ice Leads", Proceedings of the Ninth Annual Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, Ontario, p. 245-256, 1986.
20. Reimer, E.R. and J.R. Rossiter, Measurement of Oil Thickness on Water From Aircraft; A. Active Microwave Spectroscopy; B: Electromagnetic Thermoelastic Emission, Environmental Studies Revolving Fund Report Number 078, Ottawa, Ontario, 1987.
21. Aussel, J.D. and J.P. Monchalin, Laser-Ultrasonic Measurement of Oil Thickness on Water From Aircraft, Feasibility Study, Industrial Materials Research Institute Report, Boucherville, Quebec, 1989.
22. Krapez, J.C. and P. Cielo, Laboratory Evaluation of Optothermal Techniques for Remote Oil Thickness Monitoring Applications, Industrial Materials Research Institute Report IGM-RT89-404-07-C, Boucherville, Quebec, 1989.
23. Tunaley, J.K.E. and D.R. Morrcraft, "Aspects of the Detection of Oil Under Ice Using Radar Methods", Proceedings of The Ninth Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, Ontario, p. 463-474, 1986.
24. Jones, H.W., H.W. Kwan, T. Hayman and E.M. Yeatman, "The Detection of Crude Oil Under Seawater in The Arctic Ocean", Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, Ontario, p. 241-252, 1983.
25. Jones, H.W. and H.W. Kwan, "The Detection of Oil Under Ice by Ultrasound Using Multiple Element Phased Array", Proceedings of the Ninth Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, Ontario, p. 475-484, 1986.
26. Dawe, B.R., S.K. Parashar, T.P. Ryan and R.O. Worsfold, The Use of Satellite Imagery For Tracking The KURDISTAN Oil Spill, Environment Canada Report Number EPS 4-EC-81-6, Ottawa, Ontario, 31 p., 1981.
27. Alfoldi, T.T. and N.A. Prout, The Use of Satellite Data For Monitoring Oil Spills in Canada, Environment Canada Report Number EPS 3-EC-82-5, Ottawa, Ontario, 1982.
28. Hord, R.M., Remote Sensing: Methods And Applications, John Wiley and Sons, New York, 1986.